PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN $H \to 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

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THE LARGE HADRON COLLIDER

1.1 Motivation

Although the SM (Chapter **??**) is an astoundingly accurate framework, it must continue to withstand the barrage of measurements that confirm—or contradict—its predictions. After all, the truth of Nature comes from the reproducible results obtained from measurements—not from theoretical models which *may* or *may not* describe reality.

So how are measurements in particle physics obtained? Modern day physicists study the fundamental constituents of matter and their interactions by using state-of-the-art technologies combined with time-tested methodologies: by smashing tiny bits of matter together to turn them into even *tinier* bits.

1.2 The LHC at CERN

Beneath the surface of the earth (50–175 m), straddling the border between France and Switzerland, is the world's largest and most powerful particle accelerator: the Large Hadron Collider (LHC). The LHC is a circular machine and is drawn on a map in Fig. 1-1 (Left) to highlight its enormous circumference of 26.659 Km. For reference, the inscribed area of the LHC (56.7 Km^2) is almost four times greater than the area of the neighboring city of Geneva (15.9 Km^2).

The LHC is not only a particle *accelerator* but also a proton-proton (pp), proton-lead ion, and lead-lead ion *collider*. By sending one particle beam clockwise around the ring and the other beam counterclockwise, the charged particles are carefully maneuvered using 1232 dipole magnets and collimated using 506 quadrupole magnets to ultimately collide at one of 4 specific points along the LHC, as shown in Fig. 1-1 (Left, red stars). When the LHC is fully powered, each proton in the beam carries an average energy of 6.5 TeV which gives a single pp collision a center-of-mass energy of 13 TeV. This emulates the conditions theorized to exist at the beginning of the universe, which allows cosmological studies to be performed. The hugely energetic pp collisions cause the quark and gluon constituents within the protons to interact and transform into new particles. The particle debris is ejected away from the collision point and is analyzed by four major particle detectors along the LHC: A Toroidal LHC ApparatuS (ATLAS) is located at the first collision point along the LHC (*P1*), A Large Ion Collider Experiment (ALICE) at P2, the Compact

Muon Solenoid (CMS, Chapter **??**) at P5, and the LHC-beauty (LHCb) experiment at P8.

- CERN - The incredible undertaking of the LHC experiment was made possible by CERN. - LHC is part of the vast CERN complex. - Complex is built from many accelerators that feed into one another. - There are antimatter experiments, TODO:Find more experiments. Who built it? - CERN - intern'l collaboration.

Experiments around

A natural way to explore the intricacies and inner workings of the LHC is to follow the path of one of its "inhabitants"—a single proton—as it makes its way around the collider.

1.3 The Journey of a Proton at the LHC

The journey to discovery begins in an unassuming red tank of hydrogen gas (H_2) located at the main CERN site. Inside this tank, a proton—conveniently named P. Roton—and approximately TODO $\times 10^{1000000}$ other protons coexist in bound states as molecules of H2. Although the tank has a meager mass of TODO Kg, it has enough protons inside to keep the LHC RUNNING for over 200 000 years of constant operation.

Protons get injected into Series of smaller accelerators - The *Linac4*—a linear particle accelerator—accelerates hydride ions (H^-) to 160 MeV which eventually make their way into the *Proton Synchrotron Booster* (PSB). - In the PSB, each hydride ion has its electron pair completely stripped away, leaving only the bare proton TODO: mention electric field? - The protons then enter a series of circular accelerators, each machine feeding protons into the next while increasing the proton com energy by at least 1 order of magnitude. - The flow - These protons are then accelerated to 2 GeV at which point they are injected into the *Proton Synchrotron* (PS). - The PS then increases the proton energy to 26 GeV to be fed into the *Super Proton Synchrotron* (SPS). - The penultimate step is for the SPS to further energize the protons to 450 GeV a accelerates protons to com energy Finally the protons enter the LHC.

Protons are further accelerated to the maximum energy of 6.5 TeV using RF cavities to kick them. - The protons would - 1232 dipole magnets made of copper-clad niobium-titanium are used to turn the proton beams. - 392 TODO: 506? quadrupole magnets compress the proton bunches to make them more linear. - The cryogenics of the 96 t of superfluid helium-4

Finally the proton bunches approach a collision point. - Beam pipes are conjoined in an "X" shape (Figure TODO) where 2 proton bunches cross—a *bunch crossing* (BX). - Out of more than 40 million pp collisions that could have occurred, a mere 50 collisions take place on average (i.e. only 0.000 1%). - This is a testament to just how small protons truly are. - Frequency of BX: considering that proton bunches are spaced 25 ns apart, this means Just as the PS feeds protons into the SPS, which feeds protons into the LHC, so too is it being considered for the LHC to feed a new project—the 100 Km Future Circular Collider.

In the event that P. Roton does not collide with any of the oncoming protons, then it is simply "recycled" and continues going around the LHC ring for another opportunity at a pp collision.

SPECS - Luminosity - rates - data

1.4 High-Luminosity LHC

Located on the border between France and Switzerland, sandwiched between the scenic Jura mountains to the west and the sprawling city of Geneva (Genève) to the east, is CERN: the European Organization for Nuclear Research (French: *Conseil Européean pour la Recherche Nucléaire*). This international collaboration is responsible for the construction and commissioning of The completion of this world-renowned feat was only possible through the careful efforts of thousands of scientists, engineers, administrators, etc. from all over the world. At the time of this writing, CERN is associated with at least 33 countries, each of which is considered either a Member State, an Associate Member State, or an Observer.

Contrary to what some people may think, protons are not sent one by one at each other, hoping for a collision. Instead 100 billion protons are packed together into a "proton bunch". A single proton bunch is about the size of a human hair ($\approx 50\,\mu$m wide and ≈ 10 cm long). The clockwise and counterclockwise rings are filled to a maximum of 2808 proton bunches, each one spaced 25 ns apart, and then sent to collide.

It requires an incredibly strong magnetic field to turn the protons as they make their revolutions around the LHC. Recall that charged particles bend in a magnetic field, via the

Lorentz force. Therefore, the LHC is equipped with 1232 dipole magnets distributed all along the length of the beam pipe to keep the proton bunches turning in the tunnel. The cross section of such a dipole magnet is shown in Figure 1-2. Each dipole magnet is 14.3 m long, weighs 35 t, cost nearly 500 KCHF to produce, and has nearly 11 700 amps of current running through it. Only with such massive currents is it possible to generate the appropriate magnetic field strength of 8 T to keep the protons turning. The magnetic field is maintained by titanium-niobium coils, which are kept under cryogenic conditions using liquid helium to achieve the necessary temperature of 1.9 K to reach a superconducting state; this temperature is colder than that of outer space!

There are only four specific "Points" along the LHC where the proton bunches actually cross, as shown in Fig. 1-1 (Left, red stars). At each of these four points, there is a unique and gigantic particle detector to catch all the decay products from the pp collisions.

As the two bunches are just about to cross one another, they are squeezed down using quadrupole magnets, focusing the beams more tightly, increasing their chance for tasty pp collisions. During such a bunch crossing (BX), amazingly most of the protons just pass right by one another; out of the possible 100 billion possible collisions that could have occurred, Figure 1-3 shows that on average only 32 collisions occurred per BX in the LHC 2018 run, according to a particle detector called CMS, described in Chapter **??**. It should be mentioned that the luminosity of the LHC is on the order of $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

As the proton bunches whiz around the LHC, they are given "kicks" from radio-frequency (RF) cavities, which accelerate the protons to a max speed of 99.999996%c. It is analgous to the timing required when pushing someone on a swing: push at just the right time to increase their momentum. At this speed, *each proton* carries 6.5 TeV of energy, such that a single pp collision contains a monstrous center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$: more than enough energy to create new particles like top quarks, Higgs bosons, and potentially BSM particles. In order to "see" such interesting particles, one needs to detect the outgoing particles produced from pp collisions; one needs a dedicated *particle detector*... The Compact Muon Solenoid detector should do the trick.

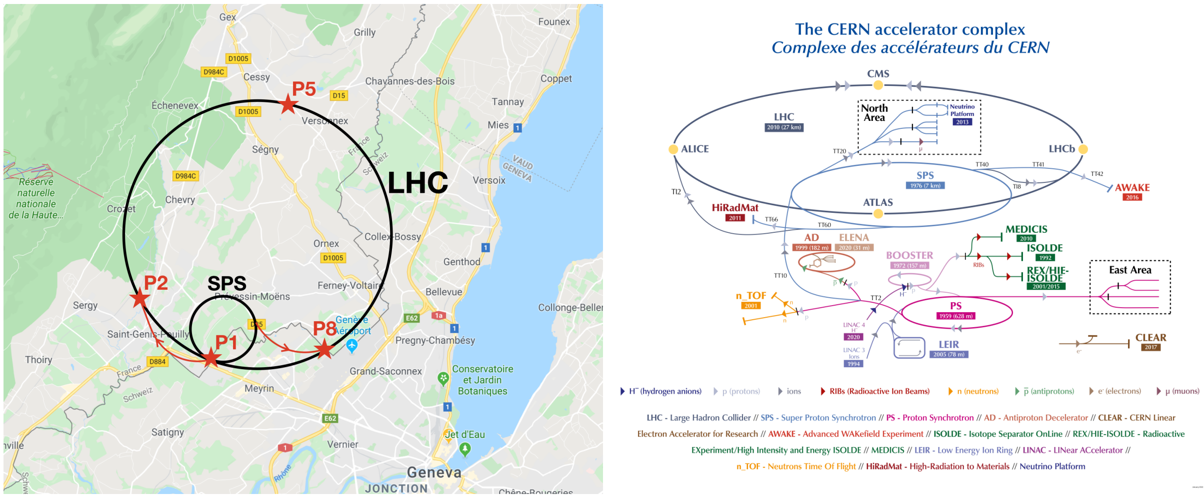

Figure 1-1. (Left) The LHC ring (bigger ring) and the Super Proton Synchrotron (smaller ring) with the nearby town of Geneva for size comparison. The four red stars indicate the pp collision points. (Right) The accelerator complex at CERN.

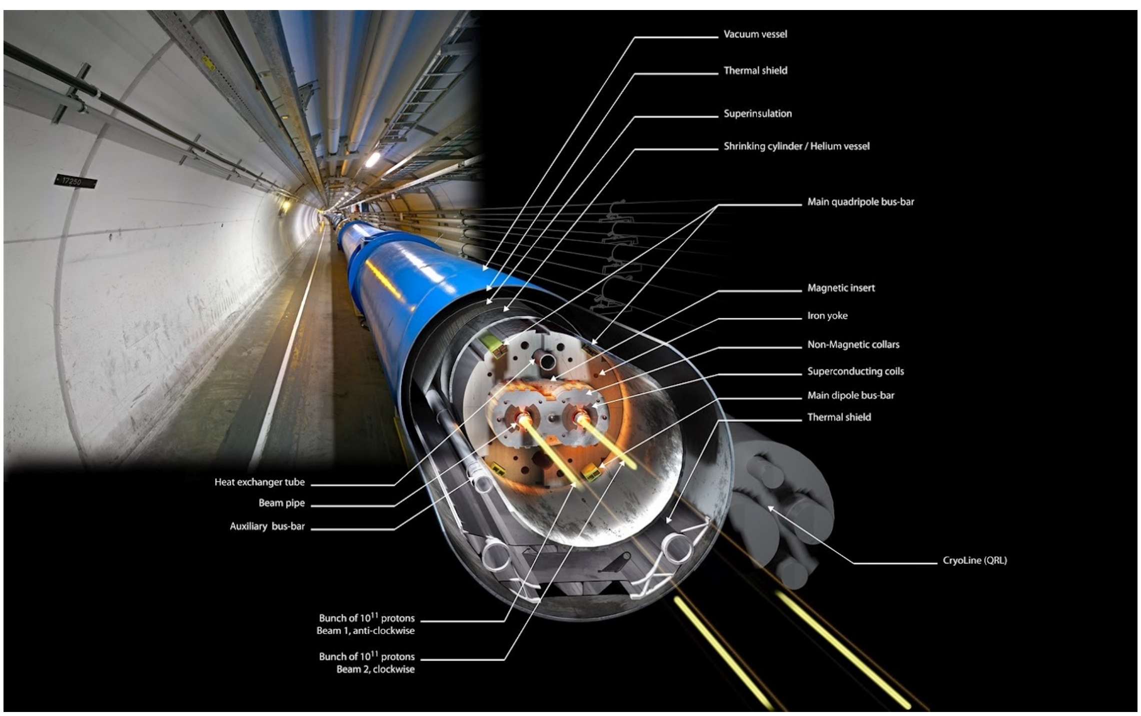

Figure 1-2. A cross section of one of the 1232 dipole magnets which span the entire length of the LHC tunnel.

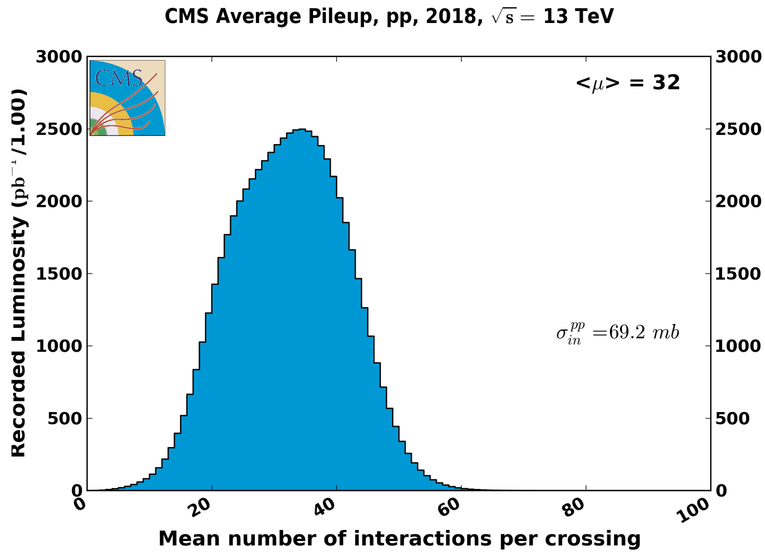

Figure 1-3. Histogram showing the distribution of the average number of pp collisions per proton bunch crossing (pile up) which CMS recorded during the LHC 2018 run.

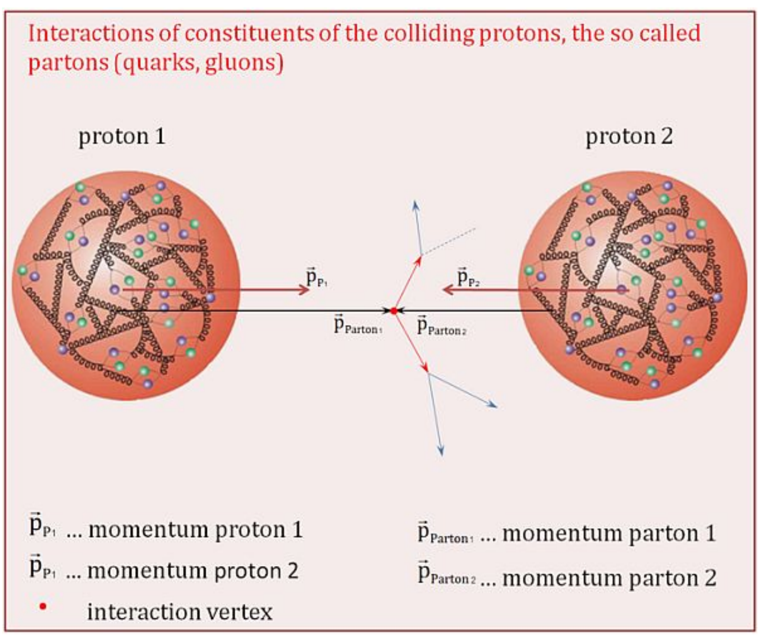

Figure 1-4. Two protons can be smashed together at very high energies to have their partons interact and convert the high energies into new kinds of matter.

REFERENCES